

Exploration of Possible Quantum Gravity Effects with Neutrinos II: Lorentz Violation in Neutrino Propagation

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Abstract. It has been suggested that the interactions of energetic particles with the foamy structure of space-time thought to be generated by quantum-gravitational (QG) effects might violate Lorentz invariance, so that they do not propagate at a universal speed of light. We consider the limits that may be set on a linear or quadratic violation of Lorentz invariance in the propagation of energetic neutrinos, $v/c = [1 \pm (E/M_{\nu QG1})]$ or $[1 \pm (E/M_{\nu QG2})^2]$, using data from supernova explosions and the OPERA long-baseline neutrino experiment.

1. Introduction

Neutrinos from astrophysical sources and long-baseline experiments are powerful probes of potential new physics. They have already been used to discover and measure the novel phenomena of neutrino oscillations, thereby establishing that neutrinos have masses [1, 2]. It has been suggested that the space-time foam due to QG fluctuations might cause energetic particles to propagate at speeds different from the velocity of light, which would be approached only by low-energy massless particles [3, 4, 5]. Any deviation from the velocity of light at high energies might be either linear or quadratic, $\delta v/c = (E/M_{QG1})$ or $(E/M_{QG2})^2$, and might be either subluminal or superluminal. Such effects are, in principle, easily distinguishable from the effects of neutrino masses, since they depend differently on the energy E .

There have been many probes of such Lorentz-violating effects on photon propagation from distant astrophysical objects such as gamma-ray bursters [6], pulsars [7] and active galactic nuclei [8]. These tests have looked for delays in the arrival times of energetic photons relative to low-energy photons, and their sensitivities improve with the distance of the source, the energies of the photons, the accuracy with which the arrival times of photons can be measured, and the fineness of the time structure of emissions at the astrophysical source. The sensitivities of these tests have reached $M_{\gamma QG1} \sim 10^{18}$ GeV and $M_{\gamma QG2} \sim 4 \times 10^{10}$ GeV for linear and quadratic violations of Lorentz invariance, respectively [9].

At least one QG model of space-time foam [10, 11] suggests that Lorentz violation (LV) should be present only for particles without conserved internal quantum numbers, such as photons, and should be absent for particles with electric charges, such as electrons [3]. Indeed, astrophysical data have been used to set very stringent limits on any LV in electron propagation. However, these arguments do not apply to neutrinos, since they are known to oscillate, implying that lepton flavour quantum numbers are not conserved. Moreover, neutrinos are often thought to be Majorana particles, implying that the overall lepton number is also not conserved, in which case QG effects might also be present in neutrino propagation [12, 13]. It is therefore interesting to study experimentally the possibility of Lorentz violation in neutrino propagation [13, 14].

Experimental probes of LV in neutrino propagation are hindered by the relative paucity of neutrino data from distant astrophysical sources, and require the observation of narrow time structures in neutrino emissions. However, there has been one pioneering experimental study of possible LV using the long-baseline MINOS experiment exposed to the NuMI neutrino beam from Fermilab, which found a range of neutrino velocities $-2.4 \times 10^{-5} < (v - c)/c < 12.6 \times 10^{-5}$ allowed at the 99% C.L. [15]. Assuming an average neutrino energy of 3 GeV, and allowing for either linear or quadratic Lorentz violation: $v/c = [1 \pm (E/M_{\nu QG1})]$ or $[1 \pm (E/M_{\nu QG2})^2]$, the MINOS result [15] corresponds in the case of linear LV to $M_{\nu QG1} > 1(4) \times 10^5$ GeV for subluminal (superluminal) propagation, and in the case of quadratic LV to $M_{\nu QG2} > 600(250)$ GeV.

In this report we describe limits on LV established in [14] by using neutrino supernova 1987a data from the Kamioka II (KII) [16], Irvine-Michigan-Brookhaven (IMB) [17] and Baksan detectors [18]. We find limits that are significantly more stringent than those established using the MINOS detector. We also assess the improved sensitivity to Lorentz violation that could be obtained if a galactic supernova at a distance of 10 kpc is observed using the Super-Kamiokande (SK) detector.

We then discuss the sensitivity to LV of the OPERA experiment at the CNGS neutrino beam from CERN. We point that substantial improvements in sensitivity of CNGS to LV in neutrino probe would result if one could exploit the RF bucket structure of the spill for neutrino events occurring in the rock upstream from OPERA. In this case, the sensitivity that could be achieved for quadratic LV is better than that obtained from supernova 1987a, and even improves on the sensitivity possible with a future galactic supernova.

2. Supernovae data analysis

In this Section we discuss the ability of supernova data to test LV. In particular, we analyze the data from the supernova SN1987a, the first supernova from which neutrinos have been detected, giving bounds at the 95% C.L.. Then we simulate a possible future galactic supernova and discuss the potential of the next generation of neutrino detectors, represented by Super-Kamiokande (SK), to improve this bound.

The detection of neutrinos from SN1987a in the Large Magellanic Cloud (LMC) remains a landmark in neutrino physics and astrophysics. Although only a handful of neutrinos were detected by the KII [16], IMB [17] and Baksan [18] detectors, they provided direct evidence of the mechanism by which a star collapses, and the role played by neutrinos in this mechanism [2]. The numbers and energies of the neutrinos observed were consistent with the expected supernova energy release of a few times 10^{53} ergs via neutrinos with typical energies of tens of MeV. A future galactic supernova is expected to generate up to tens of thousands of events in a water-Čerenkov detector such as SK, which will clarify further theories of the supernova mechanism and of particle physics [19].

We are interested in the possibility of QG effects leading to LV modifications to the propagation of energetic particles, and hence to dispersive effects, specifically a non-trivial refractive index. These dispersive properties of the vacuum would lead to an energy dependence in the arrival times of neutrinos. Therefore, any data set comprising both the time and energy

of each neutrino event can be analyzed by inverting the dispersion that would be caused by any hypothesized QG effect. The preferred value of any energy-dependence parameter would minimize the duration (time spread) of the supernova neutrino signal.

Assuming either a linear or a quadratic form of LV: $v/c = [1 \pm (E/M_{\nu QG1})]$ or $[1 \pm (E/M_{\nu QG2})^2]$, a lower limit on $M_{\nu QG1}$ and $M_{\nu QG2}$ may be obtained by requiring that the emission peak not be broadened significantly. A non-zero value of $M_{\nu QG1}^{-1}$ or $M_{\nu QG2}^{-1}$ might be indicated if it reduced significantly the duration (time spread) of the neutrino signal. The duration (time spread) of the neutrino signal can be quantified using different estimators depending on the amount of available statistics and time profile of the data set, if applicable¹. In the following, we outline two estimators for analyzing neutrino signals (see [14] for details), that we use first to quantify the limits obtainable from the SN1987a neutrino data and then the sensitivities that would be provided by a possible future galactic supernova signal.

Minimal Dispersion (MD) Method. We assume that the data set consists of a list of neutrino events with measured energies E and arrival times t (for details, see [14] and references therein). In the first method, we consider event lists with a relatively low number of events, that do not allow a reasonable time profile to be extracted. In this case we consider the time dispersion of the data set, quantified by $\sigma_t^2 \equiv \langle (t - \langle t \rangle)^2 \rangle$, where t is the time of each detected event. We then apply an energy-dependent time shift $\Delta t = \tau_l E^l$, where $\tau_l = L/cM_{\nu QGl}^l$, varying $M_{\nu QGl}$ so as to remove any assumed dispersive effects. The ‘correct’ value of the time shift τ_l should always compress the arrival times of the neutrino events. Any other (‘incorrect’) value of τ_l would spread the events in time, relative to the ‘correct’ value. We denote by τ_l^{min} the value that minimizes the spread in the arrival times. In order to estimate the uncertainties in τ_l^{min} , we use a Monte Carlo simulation to repeat the calculation of τ_l^{min} including the energy and statistical uncertainties. We then make a Gaussian fit and use it to quote best-fit parameters and errors.

Energy Cost Function (ECF) Method. This is a different analysis technique that is mostly applicable to event lists that are statistically rich. This means that one can combine the neutrino events into a time profile exhibiting pulse features that can be distinguished from a uniform distribution at high confidence level. For the analysis we first choose the most active (transient) part of the signal ($t_1; t_2$)². Having chosen this window, we scan over its whole support the time distribution of all events, shifted by $\Delta t = \tau_l E^l$, and sum the energies of events in the window. This procedure is repeated for many values of τ_l , chosen so that the shifts Δt match the precision of the arrival-time measurements, thus defining the ‘energy cost function’ (ECF). The maximum of the ECF indicates the value of τ_l that best recovers the signal, in the sense of maximizing its power (amount of energy in a window of a given time width $t_2 - t_1$). This procedure is then repeated for many Monte-Carlo (MC) data samples generated by applying to the measured neutrino energies the estimated Gaussian errors.

Neutrinos from SN1987a were detected in three detectors, KII [16], IMB [17] and Baksan [18], and the times and energies of the events are given in [14]. We calculated the minimum dispersion 1000 times for each data set, so as to include the smearing from uncertainties [14]. This analysis constrains the scale at which LV may enter the neutrino sector to be $M_{\nu QG1} > 2.7 \times 10^{10}$ GeV or $M_{\nu QG1} > 2.5 \times 10^{10}$ GeV at the 95% C.L. for the linear subluminal and superluminal models respectively. The corresponding limits for the quadratic models are $M_{\nu QG2} > 4.6 \times 10^4$ GeV or $M_{\nu QG2} > 4.1 \times 10^4$ GeV at the 95% C.L. for the subluminal and superluminal versions, respectively.

¹ Statistically poor event lists, such as that for SN1987a, the only one currently available in supernova neutrino astronomy, do not allow the time profile to be classified, because time binning is impractical and one cannot apply nonparametric statistical tests to unbinned data.

² The most active part of the signal can be chosen by fitting the binned time profile or using a Kolmogorov-Smirnov (KS) statistic [14]. In the case of a multipulse structure of the time profile, several windows may be analyzed separately.

The detection of a galactic supernova would provide improved sensitivity to the scale at which LV might enter the neutrino sector, due to an increase in the number of neutrinos which would be detected. The number of events would also increase because the current neutrino detectors are larger than those used to detect neutrinos from SN1987a. However, these effects would be partially offset because $\tau_l \propto L$ and therefore the time-energy shift will be reduced if, as expected, the supernova takes place within the galactic disc at a distance ~ 10 kpc, compared to SN1987a in the LMC at a distance of ~ 51 kpc. The closer distance would also increase the number of neutrinos that are expected to be detected, compared to SN1987a. For definiteness, we use here a Monte Carlo simulation of the Super-Kamiokande (SK) neutrino detector, but note that other neutrino detectors could also probe this physics [20]. Simulations estimate that the number of events detected in SK from a supernova at 10 kpc would be of the order of 10,000 [19]. In order to analyze at what scales LV could be probed by the detection of galactic supernova neutrinos, we made Monte Carlo simulations with various levels of linear and quadratic LV. We used the energy spectra of neutrinos from the Livermore simulation [21], which is shown in Fig. 1, and the detector properties given in [22]. We show in Fig. 2 results from our Monte Carlo simulation

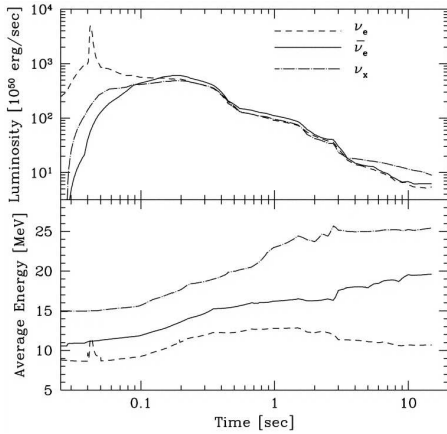


Figure 1. The neutrino energy spectra from the Livermore simulation [21].

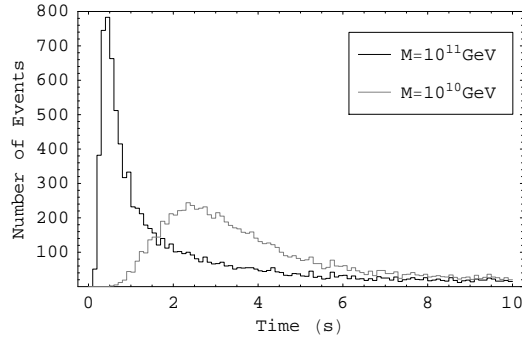


Figure 2. The time distribution of events predicted by our Monte Carlo simulation for the case of subluminal LV at the mass scales $M = 10^{10} \text{ GeV}$ and $M = 10^{11} \text{ GeV}$.

including both charged-current and neutral-current events for linear subluminal LV at the energy scales $M_{\nu QG1} = 10^{10} \text{ GeV}$ and $M_{\nu QG1} = 10^{11} \text{ GeV}$, including oscillations corresponding to the normal hierarchy and assuming that the atmospheric resonance is adiabatic. The signal has spread out and shifted in time, as we would expect.

We have applied the MD and the maximal ECF methods with various energy weightings to the Monte Carlo data with $M_{QG1} = 10^{10} \text{ GeV}$ in order to estimate the level of LV. In this way, we established that data from a future galactic supernova could place strong 95% C.L. limits on the range of $M_{\nu QG1}$ if it is lower than 10^{11} GeV . In the limit of negligible LV ($M_{\nu QG1} \geq 10^{12} \text{ GeV}$), we find the lower limits $M_{\nu QG1} > 2.2 \times 10^{11} \text{ GeV}$ and $M_{\nu QG1} > 4.2 \times 10^{11} \text{ GeV}$ at the 95% C.L. for subluminal and superluminal models, respectively. In the case of large $M_{\nu QG2}$, we find the lower limits $M_{\nu QG2} > 2.3 \times 10^5 \text{ GeV}$ and $M_{\nu QG2} > 3.9 \times 10^5 \text{ GeV}$ at the 95% C.L. for subluminal and superluminal models, respectively, in the quadratic case.

3. CNGS and the OPERA Experiment

In this Section we discuss the sensitivities to LV in neutrino propagation that could be provided by the OPERA experiment in the CNGS neutrino beam.

The energy spectrum of the calculated CNGS ν_μ flux is reproduced in Fig. 3. Its average neutrino energy is ~ 17 GeV, significantly higher than that of the NuMI beam. Since the CNGS baseline is almost identical with that of the NuMI beam, this gives some advantage to OPERA, assuming that it can attain similar or better timing properties. We recall that the CNGS beam is produced by extracting the SPS beam during spills of length $10.5 \mu\text{s}$ (10500 ns). Within each spill, the beam is extracted in 2100 bunches separated by 5 ns. Each individual spill has a $4 - \sigma$ duration of 2 ns, corresponding to a Gaussian RMS width of 0.25 ns [23].

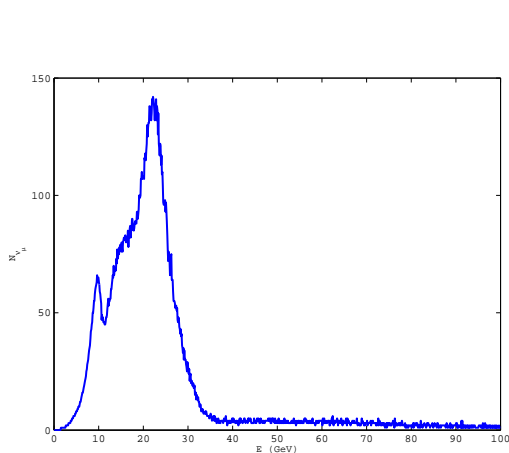


Figure 3. The expected CNGS neutrino beam energy spectrum [23].

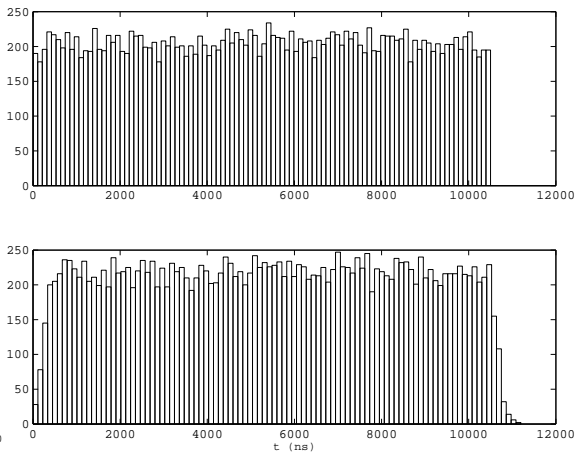


Figure 4. The time structure of events in the CNGS beam, without LV (upper panel), and with time delay at the level of $\tau = 5$ ns/GeV (lower panel).

We introduce a ‘slicing estimator’ [14], based on the fact that if some energy-dependent time delay is encoded into the time structure of the spill by propagation of the neutrinos before detection, one should observe a systematic increase in the overall time delay of events as their energies grow. Therefore, we propose cutting the energy spectrum of the neutrino beam into a number of energy slices, and searching for a systematic delay in the mean arrival times of the events belonging to different energy slices that increases with the average energy of the slice.

In order to illustrate this idea, we perform a simple exercise simulating the sensitivity of the slicing estimator for a time delay depending linearly on the neutrino energy: $\Delta t = \tau E$, assuming $\approx 2 \times 10^4$ charged-current events, as are expected to be observed in the 1.8 kton OPERA detector over 5 years of exposure time to the CNGS beam. We envisage superposing all the CNGS spills with a relative timing error δt . Since each spill has 2100 bunches, we expect about 10 events on average due to each set of superposed bunches. As a starting-point, before incorporating the relative timing error, the timing of each event has been smeared using a Gaussian distribution with standard deviation 0.25 ns, reflecting the bunch spread. We also incorporate the uncertainty in the relative timing of the bunch extraction and the detection of an event in the detector. The overall uncertainty has three components: an uncertainty in the extraction time relative to a standard clock at CERN, an uncertainty in the relative timing of clocks at CERN and the LNGS provided by the GPS system, and the uncertainty in the detector timing relative to a standard clock in the LNGS. With the current beam instrumentation, implementation of GPS and detector resolution, it is expected that this will be similar to that achieved by MINOS in the NuMI beam, namely ~ 100 ns. Such a timing error renders essentially invisible the internal bunch structure of the CNGS spill, which looks indistinguishable from a uniform distribution

generated with the same statistics, as shown in the upper panel of Fig. 4.

We next demonstrate in the lower panel of Fig. 4 the effect of a time delay during neutrino propagation at the level of $\tau_l = 5$ ns/GeV, as would occur if $M_{\nu QG1} = 4.8 \times 10^5$ GeV. This would correspond to a total delay ~ 100 ns at the average energy of the CNGS neutrino beam. We smear the events with an energy resolution of 20%, and then cut the sample into slices of about 1000 events each with increasing energies.

By making many realizations of the event sample with the Gaussian $\delta t = 100$ ns smearing, one can understand the significance of the shifts in the mean positions of the slices. Fig. 5 shows the energy dependence of the shifts in the mean timings of the slices of 1000 events with a delay $\tau_l = 5$ ns/GeV encoded. These points may be fitted to a straight line $\Delta\langle t \rangle = \tau_l \langle E \rangle + b$.

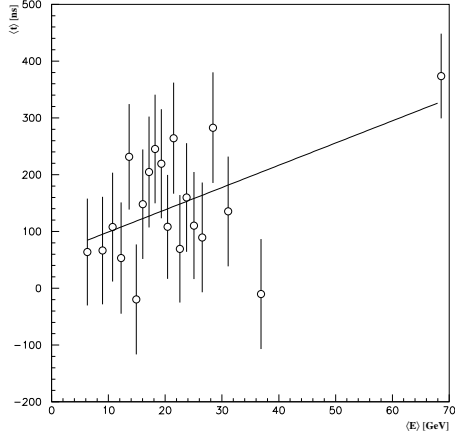


Figure 5. The measured shifts in the average arrival times of neutrinos in 1000-event slices with increasing energies, assuming a time delay during neutrino propagation at the level of $\tau = 5$ ns/GeV.

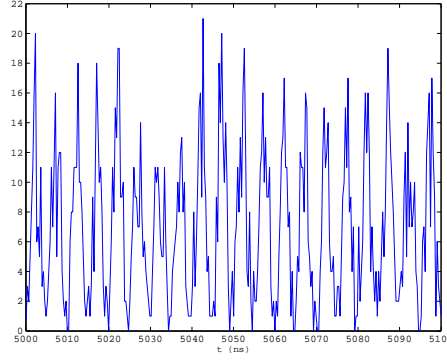


Figure 6. A simulated realization of the bunch structure for rock events, incorporating a timing uncertainty ≈ 1 ns. The histogram is binned with a resolution suitable for resolving the bunch structure.

One obtains $\tau_{95\%} = 4.9(2.6)$ ns/GeV at the 95% C.L. for the subluminal (superluminal) propagation schemes, corresponding to values of the linear Lorentz-violating scale $M_{\nu QG1} = 4.9(9.2) \times 10^5$ GeV, yielding a mean sensitivity to $M_{\nu QG1} \simeq 7 \times 10^5$ GeV. If the velocity of the neutrino depends quadratically on the energy of the neutrino, the slices should obey a parabolic fit $\Delta\langle t \rangle = \tau_q \langle E \rangle^2 + c$. In quadratic case we obtain the sensitivity $M_{\nu QG1} = 6.2(11) \times 10^3$ GeV $\simeq 8 \times 10^3$ GeV. The stability of the slicing estimator has been checked by various methods (see [14] for the details) including spill edges fitting used in MINOS analysis [15].

We recall that the OPERA detector may also be used to measure the arrival times of muons from 2×10^5 neutrino events in the rock upstream of the detector. Information on the neutrino energy is missing in this measurement. Nevertheless, one can use methods that compare overall the time shift of the simulated data to the measured time distribution of the rock events. In this spirit, applying to the 2×10^5 expected rock events the edge-fitting procedure described in [14, 15], we find a sensitivity to $M_{\nu QG1} \approx 2.4 \times 10^6$ GeV, about three times better than previously, in the case of linear energy dependence, and the same level of sensitivity for the quadratic energy dependence.

We also explored the additional sensitivity that OPERA could obtain if it could achieve a correlation between the SPS RF bunch structure and the detector at the nanosecond level. Possible techniques for doing this are outlined in details in [14]. In Fig. 6 we present one particular realization of a sample of simulated events which incorporates a relative timing error

of 1ns. Although the periodic bunch structure survives, the signal itself represents a time series with a relatively low signal-to-noise ratio. The latter implies that the proper deconvolution to extract isolated features cannot be made. In the other words, there is a problem in fitting the fine structure of the signal with an analytical function. Such a situation has been widely investigated in analyses of the temporal profiles of gamma-ray bursters (GRBs) [24]. We therefore apply a cross correlation function (CCF) method similar to that described in [24] but differing only in details of its adaptation [14]. Namely, in [14] we introduce a CCF for the temporal correlation of two time series $A(t)$ and $B(t+\tau_{l(q)})$ where $A(t)$ is a Monte Carlo simulation of the events with no dispersion effects, and $B(t+\tau_{l(q)})$ is the simulated data which has the time shift required to invert the effect of the energy-dependent dispersion. We average over several Monte Carlo simulations to include the statistical uncertainties as well as performing time and energy smearing due to the uncertainty in these measurements. We then calculate $\text{CCF}(\tau_{l(q)})$ as a function of $\tau_{l(q)}$ and find its maximum value. The value of $\tau_{l(q)}$ which maximizes the CCF is an estimate of the true value of $\tau_{l(q)}$. To find this estimate we fit a Gaussian to the peak of the resulting CCF, and deduce the sensitivity of the CCF from the precision of the position of the maximum for the Gaussian fit. In the case of linear energy dispersion, the sensitivity obtained in [14] corresponds to $M_{\nu QG1} \approx 6.6 \times 10^7$ GeV. For the subluminal case, one obtains $M_{\nu QG1} \approx 2.4 \times 10^7$ GeV. The same CCF procedure may also be applied to the quadratic case [14]. The limits deduced in this case are $M_{\nu QG2} = 3.6(4.9) \times 10^4$ GeV $\simeq 4 \times 10^4$ GeV for superluminal (subluminal) propagation models.

The CCF calculated for the rock events gives the following sensitivity levels $M_{\nu QG1} = 4.3(3.2) \times 10^8$ GeV $\simeq 4 \times 10^8$ GeV for the linear case, and $M_{\nu QG2} = 8.8(4.3) \times 10^5$ GeV $\simeq 7 \times 10^5$ GeV for the quadratic case. The sensitivity in the quadratic case is significantly better than the sensitivity estimated for a possible future galactic supernova.

4. Conclusions

We find from the SN1987a data lower limits on the scale of linear LV in the neutrino sector that are $M_{\nu QG1} > 2.68 \times 10^{10}$ GeV and $M_{\nu QG1} > 2.51 \times 10^{10}$ GeV at the 95% C.L. in the subluminal and superluminal cases respectively. The corresponding limits for the quadratic model are $M_{\nu QG2} > 4.62 \times 10^4$ GeV and $M_{\nu QG2} > 4.13 \times 10^4$ GeV at the 95% C.L. in the subluminal and superluminal cases, respectively. We have also used a Monte Carlo simulation of a galactic supernova at 10 kpc to estimate how accurately LV could be probed in the future. We have shown that it would be possible to place limits up to $M_{\nu QG1} > 2.2 \times 10^{11}$ GeV and $M_{\nu QG1} > 4.2 \times 10^{11}$ GeV at the 95% C.L. for the subluminal and superluminal cases, respectively, for linear models of LV, and $M_{\nu QG2} > 2.3 \times 10^5$ GeV and $M_{\nu QG2} > 3.9 \times 10^5$ GeV at the 95% C.L. for the subluminal and superluminal cases, respectively, for quadratic models of LV.

We find that, using standard clock synchronization techniques, the sensitivity of the OPERA experiment would reach $M_{\nu QG1} \sim 7 \times 10^5$ GeV ($M_{\nu QG2} \sim 8 \times 10^3$ GeV) after 5 years of nominal running. If the time structure of the SPS RF bunches within the extracted CNGS spills of 10.5 μ s could be exploited, which would require reducing the timing uncertainty to ~ 1 ns, these figures would be improved significantly, to $M_{\nu QG1} \sim 5 \times 10^7$ GeV ($M_{\nu QG2} \sim 4 \times 10^4$ GeV). Using events in the rock upstream of OPERA, and again assuming a time resolution ~ 1 ns, the sensitivities to LV could be further improved to $M_{\nu QG1} \simeq 4 \times 10^8$ GeV for the linear case and $M_{\nu QG2} \simeq 7 \times 10^5$ GeV for the quadratic case.

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